Water sources used by riparian trees varies among stream types
on the San Pedro River, Arizona

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Abstract

   Variation in the sources of water used by trees species has important ramifications for forest water balances. The fraction of tree transpiration water derived from the unsaturated soil zone and groundwater in a riparian forest was quantified for *Populus fremontii*, *Salix gooddingii*, and *Prosopis velutina* across a gradient of groundwater depth and stream flow regime on the San Pedro River in southeastern Arizona, U.S.A. The proportion of tree transpiration derived from different potential sources was determined using oxygen ($\delta^{18}O$) and hydrogen (δD) stable isotope analysis in conjunction with 2- and 3-compartment linear mixing models. Comparisons of $\delta^{18}O$ and δD of tree xylem water with that of potential water sources indicated that *Salix gooddingii* did not take up water in the upper soil layers during the summer rainy period, but instead used only groundwater, even at an ephemeral stream site where depth to groundwater exceeded 4 m. *Populus fremontii*, a dominant 'phreatophyte' in these semi-arid riparian ecosystems, also used mainly groundwater, but at the ephemeral stream site during the summer rainy season this species derived between 26 and 33 % of its transpiration water from upper soil layers. Similarly, at the ephemeral stream site during the summer rainy period, *Prosopis velutina* derived a greater fraction of its transpiration water from upper soil layers, than at a perennial stream site where groundwater depth was less than 2 m. Measurements of transpiration flux combined with stable isotope data revealed that *Populus fremontii* transpired a greater *quantity* of water from upper soil layers at the ephemeral than at the perennial stream site. These results imply that transpiration from groundwater and unsaturated soil layers by riparian vegetation may depend on the interaction between site conditions and species assemblage.

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1. Introduction

Riparian forests in the southwestern United States are characterized by a mixed assemblage of obligate phreatophytes (plants that send their roots into or below the capillary fringe to use groundwater) and facultative phreatophytes (plants that can also survive in upland environments where groundwater is not available). However, extreme spatial and temporal dynamics of water within riparian ecosystems in arid and semi-arid regions can place severe constraints on the ability of trees to meet transpiration requirements during key periods of the growing season. For example, groundwater pumping and surface water diversions have produced dramatic changes in stand structure and species composition of riparian areas in this region (Stromberg and Patten 1990). Successful conservation of these forests will require knowledge on the dependence of riparian species on groundwater and conversely, on the feedback between riparian vegetation and stream and groundwater dynamics. Not all woody species in these forests use only groundwater for transpiration as the term 'phreatophyte' implies. Use of growing season precipitation can vary considerably among different woody species in the riparian environment (Smith et al. 1991, Busch et al. 1992, Thorburn and Walker 1994, Kolb et al. 1997). However, many widely used hydrologic models assume that riparian trees derive water principally from the saturated zone (McDonald and Harbaugh 1988), which is clearly an oversimplification. Characterization of the conditions that promote use of alternative water sources and identification of those species most likely to use these water sources in riparian forests is necessary to accurately assess water budgets at the catchment level in semi-arid and arid basins.

1   The long-term reliability of groundwater may encourage riparian trees to develop

2   roots predominantly in the capillary fringe and saturated zone rather than throughout the

3   soil profile, especially if precipitation during the growing season is unreliable (Ehleringer

4   and Dawson 1992). Conversely, plants that maintain roots in many soil layers, or that

5   can rapidly deploy roots into moisture-rich patches in the soil, may respond

6   opportunistically to precipitation. Research on riparian trees using stable isotope analysis

7   has provided evidence for both modes of root system function. In Australia, *Eucalyptus*

8   spp. used various combinations of groundwater, rainfall-derived shallow soil water, and

9   stream water (Mensforth *et al*., 1994, Thorburn and Walker 1994, Dawson and Pate 1996,

10   Jolly and Walker 1996). Trees along a perennial, montane stream in California took up

11   water from upper soil layers early in the growing season, then used primarily

12   groundwater when soil dried (Smith *et al.* 1991). In western Arizona, *Populus fremontii*

13   and *Salix gooddingii* used groundwater throughout the entire growing season at perennial

14   and ephemeral streams, regardless of depth to groundwater (Busch *et al.* 1992).

15   However, responses of these trees to precipitation events were not assessed in this

16   Mojave Desert environment. Similarly, mature *Acer negundo* trees in northern Utah used

17   only groundwater, and did not appear to use perennial stream water or shallow soil water

18   (Dawson and Ehleringer 1991). In contrast, this species did use soil water from

19   precipitation at ephemeral and perennial stream reaches in Arizona (Kolb *et al.* 1997).

20   Although previous studies addressed various components of riparian ecosystems

21   and tree water sources, questions still remain about the integrated effects of groundwater

22   depth and flow regime on the ability of riparian trees to take up precipitation during the

23   growing season. Knowledge of species-specific responses to growing season

1   precipitation and constraints on deep and shallow root function for water uptake will

2   facilitate predictions of how habitat variation and declining groundwater affect patterns

3   of transpiration in riparian ecosystems.

4   The upland species *Quercus gambelii*, *Juniperus osteosperma*, and *Pinus edulis* in

5   the southwestern United States derived greater proportions of their transpiration water

6   from summer precipitation as the amount of these rains increased across a broad climatic

7   gradient (Williams and Ehleringer, *in press*). Intraspecific variation of this type implies

8   that the distribution of functional roots in woody species varies significantly across

9   resource supply gradients. However, the tradeoffs associated with this variation have not

10   been addressed. For instance, it is not known if development of roots in one zone of the

11   rhizosphere comes at the expense of root activity elsewhere. Additionally, plants with

12   roots deployed in upper soil layers should experience a greater amplitude of soil water

13   availability compared to plants that access a deep, stable water source. Plant predawn

14   water potential (Ψ_{pd}), therefore, should be correlated with plant water sources (Dawson

15   and Ehleringer 1998). A better understanding of the tradeoffs between plant water

16   balance and active rooting depth will help resolve linkages between groundwater, soil

17   water, and transpiration in riparian forests.

18   The riparian forest sites addressed in the current study receive a high proportion

19   (approximately 60%) of annual precipitation from summer 'monsoon' storms. Thus it

20   was predicted that at least some of the dominant riparian trees would use summer

21   precipitation. As in most riparian environment in semi-arid regions, the floodplains

22   varied in depth to groundwater that may further differentiate shallow soil water use

23   among the dominant riparian species. This study addressed seasonal patterns of water

source use by dominant riparian tree species at sites with contrasting groundwater depths

and stream flow conditions. This study was part of the Semi-Arid Land Surface

Atmosphere (SALSA) Program (USDA-ARS, Tucson, AZ) whose primary aim was to

validate models for basin-wide water balances (Goodrich *et al. this issue*). The specific

objectives of this study were to: (1) determine if riparian tree species along the San Pedro

River in southeastern Arizona use growing season precipitation; (2) assess whether depth

to groundwater influences the capacity for these trees to use precipitation; and (3)

characterize physiological consequences associated with specific rooting patterns.

2. Methods

Study sites

Three sites were selected to represent a gradient in stream flow and groundwater

availability. All sites were located within the San Pedro National Riparian Conservation

Area at elevations between 1150 and 1250 m (ca. 31° 33' N; 110° 07' W). The San Pedro

River is a low-gradient alluvial drainage that flows from Sonora, Mexico north to the

Gila River in southern Arizona. Mean precipitation at the three sites is 330 mm per year,

with 60% of the rain falling in the summer and most of the remainder falling in winter

months (NOAA 1996). The hydrologic regime at the three sites was perennial (Lewis

Springs), intermittent (Boquillas Ranch), and ephemeral (Escapule Wash). The riparian

floodplain vegetation consisted of *Populus fremontii* (Fremont cottonwood) and *Salix*

gooddingii (Goodding willow) as the dominant and sub-dominant overstory species. In

this region these species, both classified as obligate phreatophytes, generally form a

narrow gallery forest in active floodplains (Stromberg 1993). *Prosopis velutina* (Velvet

1   mesquite) was present as a sub-dominant tree and as an understory shrub within the

2   *Populus/Salix* gallery forests. *Prosopis velutina* is a facultative phreatophyte that also

3   occurs in xeric upland sites where groundwater is unavailable. Hereafter, these taxa will

4   be referred to as *Populus*, *Salix*, and *Prosopis*.

5

6   Sampling Methods

7   Between five and eleven tree clusters with each of the three species present were

8   randomly selected at each site. Clusters were not considered blocks in a statistical sense

9   because species were analyzed separately. Trees were sampled in spring (April 19-24),

10 summer (June 7-11, July 9-11, August 8-11) and fall (September 20-27) in 1997. April

11 sampling occurred after *Populus* experienced spring leaf-flush. June and July sampling

12 periods coincided with the annual dry season for this region. Sampling in August was

13 performed during the height of the growing season and after a large monsoon

14 precipitation event which did not produce over-bank flooding. During this single

15 precipitation event, 27 mm of rainfall was measured at the perennial stream site, which

16 fell during a single hour; trees were sampled 7, 8, and 10 days after the rainfall event at

17 the ephemeral, intermittent and perennial stream sites, respectively. September sampling

18 followed a series of storms that produced over-bank flooding along the perennial reach at

19 the end of the growing season.

20   Stable isotopes of oxygen in xylem water extracted from twigs were used as

21 natural tracers for determining the fraction of water taken from groundwater and

22 unsaturated soil layers (Ehleringer and Dawson 1992, Brunel *et al.* 1995). Plant stems of

23 approximately 0.5 cm in diameter were sampled at midday from sunlit branches and

1   stored in airtight glass vials for subsequent analysis of hydrogen and oxygen isotope

2   ratios (δD and $\delta^{18}O$). Soils were collected at each site from 5-, 10-, 25-, 50-, and 100-cm

3   depths for analysis of δD and $\delta^{18}O$ of water and gravimetric water content (θ_g). Local

4   floodplain groundwater was collected from wells at each sampling period and at all sites.

5   At the perennial reach, regional groundwater was collected from a deep (11 m) well

6   located approximately 300 m from the stream and outside the local floodplain.

7   Precipitation was collected at all sites in standard rain gauges that contained a layer of

8   mineral oil to minimize evaporation. These integrated precipitation samples were

9   collected monthly throughout 1997. A Scholander-type pressure chamber (PMS,

10   Corvalis, OR) was used to measure predawn leaf water potentials (Ψ_{pd}) on every

11   sampling date.

12

13   <u>Stable Isotope Analysis</u>

14   Water was extracted from plant stems and soils by cryogenic vacuum distillation

15   (Ehleringer and Osmond 1989). Plant, soil, stream, and groundwater samples were

16   analyzed for oxygen isotope ratios ($\delta^{18}O$) on a Finnigan Delta-S isotope ratio mass

17   spectrometer using CO_2 equilibration (University of Arizona Geosciences Stable Isotope

18   Facility). A subset of samples was also analyzed for hydrogen isotope ratios (δD) using a

19   chromium reduction furnace (HD-Device, Finnigan-Mat, Breman, Germany) to convert

20   liquid water to hydrogen gas.

21

<u>Data analysis</u>

Plant $\delta^{18}O$ values were compared with those of soil water from different depths and groundwater to determine sources of plant transpiration water. One-sided t-tests ($\alpha =$ 0.05) were used to determine if mean $\delta^{18}O$ of a species at a given site was more positive (enriched) than $\delta^{18}O$ of floodplain groundwater in June, July and August. Normality of $\delta^{18}O$ data was determined with the Shapiro-Wilk test. δD-$\delta^{18}O$ relationships of isotopic values from 10-, 25- and 100-cm soil depths, extracted plant water, rainfall and groundwater were used to determine further differences in plant water source use (Craig 1961, Clark and Fritz 1998). Source waters with similar $\delta^{18}O$ or δD values may have different δD-$\delta^{18}O$ relationships due to evaporation conditions.

Although $\delta^{18}O$ and Ψ_{pd} values are presented for all sampling periods, statistical analyses were restricted to June, July and August. This restriction was due to phenological differences among species (*Prosopis* and *Salix* were not fully leafed out in April), and because, large storms produced over-bank flooding at the perennial site in September. Over-bank flooding percolated through the soil creating similar $\delta^{18}O$ values to a depth greater than 1 m. Therefore, it was not possible to distinguish use of monsoon precipitation from groundwater and floodwater use. Multivariate analysis of variance (MANOVA; $\alpha = 0.05$) was used to analyze the effect of site and sampling date (June, July and August) on the difference between plant $\delta^{18}O$ and groundwater $\delta^{18}O$ for each species (Von Ende 1993). This difference was used to standardize plant response across sites even when there were shifts in local groundwater $\delta^{18}O$ values. ANOVA models (α = 0.05) were used to compare sites within years if MANOVA revealed a significant interactive effect. Since it was expected that sampling date would produce an effect on

1   $\delta^{18}O$, differences within a site across dates were not analyzed. Contrasts ($\alpha = 0.05$) were

2   used to determine differences between sites. Plots of residuals indicated that calculated

3   $\delta^{18}O$ differences were linear and normally distributed with homogenous error variances,

4   thus meeting the assumptions of MANOVA.

5   In cases where plant $\delta^{18}O$ differed significantly from that of local groundwater,

6   the fraction (*f*) of total plant xylem water derived from shallow soil layers (0-50 cm) was

7   calculated using a 2-compartment linear mixing equation of the form:

8

9   [Eqn. 1] $\delta^{18}O_t = f(\delta^{18}O_s) + (1\text{-}f)(\delta^{18}O_{gw})$

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11 where $\delta^{18}O_t$ was the measured $\delta^{18}O$ of tree xylem sap, $\delta^{18}O_s$ was a weighted average of

12 the measured $\delta^{18}O$ values of soils sampled at 5-, 10-, 25-, and 50-cm depths. Soil $\delta^{18}O$

13 values were weighted by gravimetric water content (θ_g) at each depth by dividing mean

14 θ_g at each depth by the sum of θ_g at all depths. $\delta^{18}O_{gw}$ was the measured $\delta^{18}O$ value of

15 groundwater. The equation was solved for *f*, the fraction of total plant water obtained

16 from water in shallow soil layers. Differences between sites were determined for each

17 species using t-tests.

18 At the intermittent stream site, the use of a 2-compartment model was

19 inappropriate because of the existence of a third source of plant water. Therefore a 3-

20 compartment linear mixing model was used. This was done using plant and source $\delta^{18}O$

21 and δD to produce two equations for tree water source. These two equations, in

22 combination with a third equation (for constraining the sum of the source fractions to

23 one) produced a system of three equations and three unknown variables of the form:

1

2   [Eqn. 2] $\delta^{18}O_t = a(\delta^{18}O_{S1}) + b(\delta^{18}O_{S2}) + c(\delta^{18}O_{S3})$

3   [Eqn. 3] $\delta D_t = a(\delta D_{S1}) + b(\delta D_{S2}) + c(\delta D_{S3})$

4   [Eqn. 4] $1 = a + b + c$

5

6   where $\delta^{18}O_t$ and δD_t are the oxygen and deuterium values of extracted plant water. The

7   subscripts S1, S2, S3 are sources 1, 2, and 3, respectively. *a,b,c* are the fractions of total

8   plant xylem water derived from sources 1, 2, and 3. Equations were solved

9   simultaneously using algebraic substitution. Results were checked using MatLab

10   (MathWorks, Inc., Natwick, MA).

11   To analyze effects of site and date (June, July, August) on Ψ_{pd}, MANOVA,

12   ANOVA and contrasts were used as described above. Data were transformed as

13   necessary to meet the assumptions of MANOVA based on inspection of residual plots.

14   Non-transformed values are presented in the figures and text. For each species within a

15   site, linear regression analysis was used to quantify the relationship between Ψ_{pd} and

16   $\delta^{18}O$ measured throughout the growing season.

17

18   **3. Results**

19   Mean depth to groundwater was 1.80, 2.67 and 4.26 m at the perennial,

20   intermittent, and ephemeral stream sites, respectively (Table 1). Median stream flow

21   along the perennial reach of the San Pedro River measured downstream of our study site

22   at the Charleston gauge for the period January 1997 to October 1997 was 0.2 m^3 s^{-1}.

23   (Tayadon *et al.* 1998). Stream flow was observed along the intermittent reach for 11

months of 1997, but there was no flow in July. Flow occurred only briefly during storm

events at the ephemeral stream site. Stream flow was observed twice in August at this

site, but may have occurred during other storms as well.

Monsoon rains had $\delta^{18}O$ values ranging from 2.0 to –3.5 (‰) (Fig. 1), while

winter precipitation had more negative $\delta^{18}O$ values ranging from -4.4‰ to –8.7‰ (data

not shown). $\delta^{18}O$ values of groundwater sampled from the local floodplain did not vary

much over the growing season at the perennial and ephemeral reach, averaging -8.3 ± 0.2

‰ (± 1 SE) and –8.4 ± 0.2 ‰, respectively (Fig. 1). In late September, after a

particularly large series of storms, groundwater at the ephemeral reach was enriched

(more positive) ($\delta^{18}O$ = -7.8 ‰) relative to previous sampling periods. $\delta^{18}O$ of local

floodplain groundwater at the intermittent stream site varied substantially (Fig. 1).

During April, June, and July, the local floodplain groundwater ($\delta^{18}O$ = -7.3 ± 0 .15 ‰)

isotopically resembled $\delta^{18}O$ of winter precipitation (-6.1 ± 0.35 ‰) at the intermittent

stream site. However, during the summer rainy season in response to storm and flow

events, $\delta^{18}O$ of local floodplain groundwater at this site was substantially enriched (-4.9 ±

0.07 ‰) and reflected $\delta^{18}O$ of monsoon precipitation and recent stream flow. Isotopic

composition of regional groundwater was stable throughout the growing season, with

mean $\delta^{18}O$ of –9.7 ± 0.07 (‰). Stream water is tightly linked with groundwater in this

region, and $\delta^{18}O$ values of stream water (data not shown) were generally related to those

of floodplain groundwater; therefore, stream water was not treated as a separate source.

$\underline{\delta^{18}O \text{ of tree xylem water}}$

Salix gooddingii

1   *Salix* (willow) exhibited little variation in water-source use over the growing

2   season among the three sites and relied predominantly on groundwater (Fig. 1). $\delta^{18}O$

3   values of this species were not significantly enriched above those of groundwater at any

4   site or any sampling period ($p > 0.13$). $\delta^{18}O$ values of *Salix* were not different among

5   sites or sampling periods ($p > 0.07$), and this species did not appear to use significant

6   amounts of precipitation at any site, even in August after a significant precipitation event.

7   Although $\delta^{18}O$ values of *Salix* increased at the intermittent and ephemeral stream sites in

8   August, these shifts mirrored changes in groundwater $\delta^{18}O$ within the floodplain.

9

10   *Populus fremontii*

11    $\delta^{18}O$ values of xylem water in *Populus* (cottonwood) varied seasonally and

12   apparently responded to monsoon precipitation events (Fig. 1). *Populus* relied on

13   groundwater during the rainless period in June and July, but showed evidence of water

14   use from shallow soil during the rainy season. The $\delta^{18}O$ values of *Populus* did not differ

15   from that of floodplain groundwater in June and July at any of the three sites ($p > 0.19$).

16   However, use of water from shallow soil layers during the summer rainy period (August)

17   developed differently among the three riparian habitats studied. These habitat-related

18   differences in $\delta^{18}O$ of *Populus* were reflected statistically in a significant interaction

19   between sampling date and site ($p = 0.05$). Specifically, the difference between $\delta^{18}O$ of

20   *Populus* and that of floodplain groundwater varied between all sites in August ($p <$

21   0.0025). $\delta^{18}O$ values of *Populus* were 0.4 ‰ more positive than that of floodplain

22   groundwater at the perennial stream site ($p = 0.01$), and showed the greatest difference

23   (+2.1‰) above floodplain groundwater at the ephemeral stream site ($p < 0.0001$).

1 However, $\delta^{18}O$ of *Populus* was more negative than that of floodplain groundwater at the

2 intermittent site (2-sided t-tests; p < 0.03).

3

4 *Prosopis velutina*

5   Similar to *Populus*, water sources of *Prosopis* (mesquite) varied seasonally in

6 response to monsoon rain events (Fig. 1). $\delta^{18}O$ values of *Prosopis* were affected by the

7 interaction between site and sampling date (p = 0.04). During the dry season (June and

8 July), mean $\delta^{18}O$ of *Prosopis* was similar to floodplain groundwater (p > 0.12) except at

9 the ephemeral stream site in July (p = 0.04). *Prosopis* $\delta^{18}O$ values were enriched relative

10 to floodplain groundwater in August at the intermittent and ephemeral site (p < 0.02)

11 indicating use of monsoon-derived shallow soil water. Prosopis $\delta^{18}O$ did not differ from

12 floodplain groundwater at the perennial stream site in August (p = 0.11). However, there

13 was considerable variation among $\delta^{18}O$ values of individual trees at the perennial stream

14 site that indicated some trees used groundwater while others used a combination of

15 shallow soil water and groundwater. This was reflected in the difference between plant

16 $\delta^{18}O$ and groundwater $\delta^{18}O$. These data indicated that $\delta^{18}O$ values of *Prosopi*s were

17 similarly enriched relative to floodplain groundwater in June and August at the

18 intermittent and perennial stream sites (p > 0.11). However, trees at the ephemeral site

19 were more enriched relative to groundwater than at the other two sites (p < 0.01).

20

21 <u>δD-$\delta^{18}O$ plots</u>

22   Isotope values of *Populus*, *Salix*, and *Prosopis* water in δD-$\delta^{18}O$ space plotted

23 near groundwater and soil water from 100-cm depth at the perennial stream site (Fig. 2).

1   At the intermittent stream site, values for *Populus* and *Salix* were between local

2   floodplain groundwater (sampled in July and August) and water from the 100-cm depth,

3   but *Prosopis* plotted between soil water from the 10-, 25-and 100-cm depths. *Salix*

4   values were similar to those of groundwater at the ephemeral stream site and *Populus*

5   values were between those of groundwater and 100-cm soil demonstrating potential use

6   of shallow soil water. *Prosopis* plotted with soil water from the 25- and 100-cm at the

7   ephemeral stream site.

8

9   δ^{18}O and gravimetric content of soil water

10   The large rainfall event in August caused gravimetric water content (θ_g) in the

11   shallow soil layers to increase at all sites (Fig. 3). θ_g increased from 5% in June to 18%

12   in August in the upper 10 cm at the perennial reach, whereas θ_g at this depth increased

13   from 2% to 6% and from 2% to 8% at the ephemeral and intermittent stream sites,

14   respectively. Changes in θ_g at the 25-, 50-, and 100-cm depths between June and August

15   were minimal along the perennial and intermittent reaches. θ_g increased slightly over the

16   same period at the 25- and 50-cm depths along the ephemeral reach. Soil water δ^{18}O

17   values were more positive in upper than in lower layers (Fig. 3), and became more

18   negative with depth. δ^{18}O values at 100 cm (-8.0‰) were similar to those of

19   groundwater at the perennial site, however δ^{18}O values at the same depth were

20   approximately –6.0‰ at the ephemeral and intermittent reaches. δ^{18}O values of soil

21   water in the upper 25 cm of soil resembled δ^{18}O of summer monsoon rainfall (Fig. 1).

22

23   Fraction of transpiration water derived from shallow soil

1    $\delta^{18}O$ of *Salix* did not differ from groundwater at any period and therefore the

2   fraction of water derived from shallow unsaturated soil layers was assumed to be zero.

3   When $\delta^{18}O$ of *Prosopis* and *Populus* differed from groundwater at the perennial and

4   ephemeral stream sites, the percentage of shallow (0-50 cm) soil water use was calculated

5   from the 2-compartment mixing model (Eqn. 1 and Table 2). Initially, the percentage of

6   transpiration water derived from shallow soil was calculated using $\delta^{18}O$ of floodplain

7   groundwater. However, trees at all sites appeared to have access to a source of water that

8   was more negative in $\delta^{18}O$ than local floodplain groundwater, such as regional

9   groundwater. This produced negative values for soil water use for three trees, which

10   were set to zero. Therefore, the average of local floodplain groundwater and regional

11   groundwater $\delta^{18}O$ was used for comparison, which may overstate the percentage of soil

12   water used by *Populus* and *Prosopis*. The average difference between the two models

13   was 7%.

14   In August after a summer rainfall event, *Populus* derived 8 to 16% of its

15   transpiration from shallow soil layers at the perennial stream site and between 26 to 33%

16   from soil water at the ephemeral stream site (Table 2). The proportion of *Populus*

17   transpiration water from shallow soil layers at the perennial site was significantly less

18   than that at the ephemeral stream site ($p < 0.03$). After the August rain event, shallow

19   soil water comprised 53 to 57% of transpiration water of *Prosopis* at the ephemeral

20   stream site. (Table 2). *Prosopis* was not different from groundwater ($p = 0.11$) at the

21   perennial site therefore mixing was assumed to be zero. In July at the ephemeral stream

22   site, $\delta^{18}O$ of *Prosopis* was significantly enriched relative to floodplain groundwater, but

since shallow soil water content was low ($< 2\%$) at this time, this source was unlikely to

have contributed to plant transpiration.

The fraction of transpiration water derived from shallow soil layers was

calculated with the 3-compartment mixing model [Eqn. 2-4] at the intermittent site.

Groundwater $\delta^{18}O$ at this site changed substantially in August from prior periods (Fig.1),

yet many trees in August had $\delta^{18}O$ values comparable to floodplain groundwater sampled

in June and July. It appears that the August runoff moving through the stream channel

flowed laterally through the gravelly substrate at this site, creating a saturated zone of

water that was perched above the floodplain groundwater and had more positive $\delta^{18}O$

values than the underlying aquifer. Therefore, $\delta^{18}O$ values from three sources were used

in the model: shallow soil water in August; groundwater sampled in August; and

floodplain groundwater sampled in July. If $\delta^{18}O$ of a species differed significantly from

$\delta^{18}O$ of groundwater sampled in August then the 3-compartment mixing model was

applied. $\delta^{18}O$ of *Prosopis* was enriched relative to August groundwater (p=0.02).

However, $\delta^{18}O$ of *Populus* was more negative than August groundwater (p = 0.03). $\delta^{18}O$

of *Salix* did not differ from August groundwater, and therefore shallow soil water use was

assumed to be zero. *Prosopis* used 67% of the perched August groundwater, 30%

shallow soil water, and 2% of the deeper floodplain groundwater (Table 3). *Populus*

fremontii used –5% of the perched August groundwater, 9% shallow soil water, and 97%

of the deeper floodplain groundwater (Table 3). Negative percentages are an artifact

produced by inherent matrix sensitivity. The 3-compartment mixing model had high

matrix sensitivity, which produced large standard errors (Table 3). This was likely due to

the limited variation in the isotopic composition of water sources. To synthesize 2- and

1   3-compartment model results and provide a conceptual interpretation of root function in

2   this system, the fraction of transpiration water derived from shallow soil water was

3   plotted in relation to groundwater depth (Fig. 4).

4

5   <u>Predawn water potential</u>

6   Predawn water potentials (Ψ_{pd}) in *Salix* and *Populus* were high (between –0.75

7   and –0.25 MPa) and changed little over the growing season (Fig. 5). These two species

8   apparently had access to groundwater even at the ephemeral stream site where

9   groundwater depth averaged 4 m. In June, when stream flow was still present and

10   groundwater tables were less than 3 m deep at the intermittent site (Table 1), the effect of

11   site ($p < 0.045$) on Ψ_{pd} was consistent across all species. During June, Ψ_{pd} values did not

12   differ between the perennial and intermittent reaches ($p > 0.12$) and trees at these sites

13   exhibited higher water potentials relative to those at the ephemeral stream site ($p < 0.02$).

14   Ψ_{pd} of *Salix* and *Populus* did not vary between sites in July ($p > 0.10$). In August, *Salix*

15   and *Populus* Ψ_{pd} values were similar at the ephemeral and perennial reaches ($p > 0.73$),

16   but both species exhibited slightly higher water potentials along the intermittent reach

17   compared to those measured at the other two sites ($p < 0.05$). Ψ_{pd} of *Prosopis* showed

18   considerable seasonal variation (Fig. 5). The lowest Ψ_{pd} values (between –1 to –1.75

19   MPa) were observed in July just before the onset of the summer rainy period. The lowest

20   Ψ_{pd} values in *Prosopis* during the dry season were observed at the intermittent stream

21   site, but did not differ significantly from those at the ephemeral site ($p = 0.27$). In July,

22   *Prosopis* along these reaches had lower water potentials than at the perennial reach ($p =$

23   0.0005).

1   The relationship between Ψ_{pd} and $\delta^{18}O$ of xylem water during the growing season

2   was evaluated for trees at the perennial and ephemeral stream sites. Mean values at each

3   sampling period are shown (Fig.6), however regression analyses were based on all

4   observations. There were no significant relationships between these variables at either of

5   the two sites in *Salix* (p > 0.09). Ψ_{pd} and $\delta^{18}O$ likewise were not correlated in *Populus*

6   and *Prosopis* at the perennial stream site. However, at the ephemeral stream site,

7   seasonal changes in water source availability that produced enriched $\delta^{18}O$ values of plant

8   were accompanied by less negative Ψ_{pd} values for both *Populus* (p = 0.0091; Ψ_{pd} = -0.14

9   + 0.04 $\delta^{18}O$, r^2 = 0.15) and *Prosopis* (p = 0.0007; Ψ_{pd} = 0.02 + 0.17 $\delta^{18}O$, r^2 = 0.43).

10

11

12   **4. Discussion**

13   Reed (1988) classified these dominant species of low-elevation riparian

14   ecosystems in southern Arizona as obligate wetland (*Salix gooddingii*), facultative

15   wetland (*Populus fremontii*) and facultative upland (*Prosopis velutina*) based on their

16   probability of occurrence within the heterogeneous floodplain environment. This study

17   provides new insight into belowground responses of these species across sites with very

18   different patterns of groundwater availability and within a climatic region that receives a

19   substantial input of precipitation late in the growing season from the regional monsoon.

20   Within this setting, substantial variation among species and populations was found for

21   fractional use of soil water derived from these late summer storms. Sites where

22   groundwater was deep and stream flow duration was intermittent or ephemeral promoted

23   greater fractional use of soil water by *Populus* and *Prosopis*, but not *Salix*. This study, as

1   well as others (Dawson and Ehleringer 1991, Smith *et al.* 1991, Busch *et al.* 1992,

2   Mensforth *et al.*, 1994, Thorburn and Walker 1994, Dawson and Pate 1996, Jolly and

3   Walker 1996, Kolb *et al.* 1997), confirms that 'phreatophytes' encompass a wide

4   spectrum of functional types that respond uniquely to spatial and temporal variation in

5   the distribution of available water in the rhizosphere.

6   *Salix gooddingii* appeared to be most critically tied to groundwater among the

7   three species examined at our sites within the San Pedro River drainage system. Predawn

8   leaf water potentials in this species were high and did not change in response to seasonal

9   inputs of precipitation, and isotopic composition of xylem water mirrored that of

10 groundwater in the local floodplain aquifer. *Salix* apparently used water only from the

11 saturated zone or capillary fringe above the water table (Figs.1 and2), and therefore did

12 not respond to precipitation, even at the ephemeral stream site where groundwater depth

13 was greater than 4 m. *Salix* apparently develops roots for water uptake only in the

14 capillary fringe or saturated zone in these alluvial soils.

15   *Populus fremontii* and *Prosopis velutina* exhibited greater flexibility for use of

16 precipitation than did *Salix* along the San Pedro River. Use of monsoon precipitation

17 may have reduced water stress as evidenced by the relationship between Ψ_{pd} and $\delta^{18}O$ in

18 these species at the ephemeral stream site (Fig. 6). Greater depth to groundwater was

19 associated with greater fractional use of soil water during the monsoon season for these

20 species (Fig. 4). Thus, groundwater depth may be a good predictor of fractional water

21 source use in this ecosystem. *Prosopis* exhibited a linear response in the proportion of

22 soil water used for transpiration along a gradient of greater depth to groundwater. The

23 response of *Populus* indicated that this species used shallow soil water at all sites, but

used a greater proportion of soil water at the ephemeral stream reach when depth to

groundwater exceeded 4 m. *Populus* potentially exhibits a threshold response in contrast

to the linear response observed in *Prosopis.* In contrast, Busch *et al.* (1992) observed no

shallow soil water use by *Populus* on the Lower Colorado and Bill Williams Rivers in

western Arizona. Our sites in southeastern Arizona receive summer precipitation inputs

substantially greater than in the arid Mojave desert, where Busch *et al.* conducted their

study. Leaffler and Evans (1999) found that adult *Populus* along the Rio Grande River

floodplain in central New Mexico responded photosynthetically to growing season

precipitation in years when stream flow along the river was low, but not when stream

flow was high. Temporal variation for precipitation use in *Populus* observed in the Rio

Grande study apparently was similar to the spatial variation that was observed along the

San Pedro River.

     Prosopis velutina exhibited substantial use of soil water during the summer rainy

period at the intermittent and ephemeral stream sites (fig. 4). δD-$\delta^{18}O$ plots (Fig. 2) from

ephemeral and intermittent stream reaches indicated that soil water from the 10-, 25- and

100-cm depths were important sources of transpiration water for this species. Along the

perennial reach the amount of shallow soil water use was assumed to be zero because

$\delta^{18}O$ was not different than that of floodplain groundwater (Fig. 4). This was likely due

to the high variability in $\delta^{18}O$ values of *Prosopis* at this site, which indicated that some

individual trees were using shallow soil water (up to 54%), while several trees relied

solely on groundwater. *Prosopis* apparently is highly flexible in its use of various water

sources. *Prosopis* predawn water potentials (Fig. 5) declined abruptly in July when water

table levels dropped and stream flow ceased at the intermittent site (see also Stromberg *et*

1   *al.* 1993). However, monsoon rains quickly ameliorated water stress in this species at all

2   sites. These data suggest that *Prosopis* may not develop extensive roots into saturated

3   zones within the soil profile and likely uses water from the capillary fringe.

4   The amount of summer rainfall in southeastern Arizona is enough to promote soil

5   water use in *Populus fremontii*. While the proportion of soil water use was higher at sites

6   with greater depth to groundwater, isotopic data do not indicate whether the *amount* of

7   soil water extracted by these trees differed between sites. This is an important distinction

8   because the amount of water gained from a soil compartment by root systems illustrates

9   the potential constraints and allocation tradeoffs that may explain root system dynamics

10 in these heterogeneous environments. The amount of water moving through *Populus*

11 trees from shallow soil layers was calculated by multiplying the fraction of xylem water

12 from this source and maximum sap flux in August at the perennial and ephemeral stream

13 sites. Sap flux data were obtained from Schaeffer and Williams (*this issue*) using the

14 same trees that were sampled for water sources. Three trees of similar size (0.5 –0.8 m

15 stem diameter) were selected at each site to minimize tree size effects. The total amount

16 of transpiration flux derived from soil water based on this calculation was 2.8 and 10.5 g

17 cm^{-2} sapwood area hr^{-1} at the perennial and ephemeral stream sites, respectively. Based

18 on this simple calculation, nearly four times as much water moving through the sapwood

19 of *Populus* trees was coming from shallow soil at the ephemeral stream site compared to

20 that at the perennial stream site. However, maximum sap flux was approximately the

21 same at the perennial and ephemeral stream reaches (35.0 and 40.7 g cm^{-2} day^{-1},

22 respectively). Total daily transpiration was compared by selecting days with similar solar

23 radiation and vapor pressure deficit. Total transpiration flux was 415.9 and 458.9 g cm^{-2}

1   day^{-1} at the perennial at ephemeral stream sites, respectively. Hence, 382.7 and 338.9 g

2   cm^{-2} day^{-1} was derived from groundwater, and 33.2 and 119.1 g cm^{-2} day^{-1} were derived

3   from shallow soil water at the perennial and ephemeral reach respectively. Total water

4   use was similar, but the amount of water from shallow soil layers was greater, while the

5   amount from groundwater was less at the ephemeral reach relative to the perennial reach.

6   Root excavation studies of *Populus* trees along the Mojave River in southern California

7   (G. C. Lines, *pers. comm.*) revealed a greater percentage (between 10-50%) of roots in

8   the upper meter of soil at sites where groundwater levels were more than 3 m in depth,

9   compared to sites where groundwater was only 1.5 m deep. Taken together, these data

10   suggest that there may be allocation tradeoffs associated with deploying roots in a

11   particular soil layer. Exploitation of groundwater may come at the expense of water use

12   from other sources, or, alternatively, when groundwater becomes deep or unreliable, trees

13   may develop more shallow roots to exploit other water sources.

14   Declining groundwater in the San Pedro River system will have a strong negative

15   impact on the survival of *Salix*, because water sources appear to be limited to

16   groundwater. If mature *Populus* is able to continue deep root growth during groundwater

17   recession by augmenting transpiration needs with precipitation taken up by shallow

18   lateral roots, this species may be able to tolerate some recession of groundwater depth.

19   However, it appears that *Populus* must keep roots in the saturated zone to maintain high

20   predawn water potentials. Therefore, persistent long-term declines in groundwater levels

21   will likely limit this species as well (*see also* Stromberg *et al.* 1996). *Prosopis* is highly

22   flexible in its use of water sources and is likely to become more dominant in the riparian

23   landscape if declining groundwater levels persist. However, *Prosopis* tree growth may be

limited in stature relative to historic riparian mesquite woodlands if groundwater is

limited (Stromberg *et al.* 1993, Stromberg 1993b).

In conclusion, some riparian trees, even those commonly associated with shallow groundwater, can use substantial amounts of precipitation to meet transpiration requirements. One of the main goals of the SALSA program is to estimate and model transfer of groundwater *via* riparian evapotranspiration on a basin-wide scale (*see* Goodrich *et al.*, *this issue*). These data suggest that species composition in riparian forests (abundances of *Salix*, *Populus*, and *Prosopis*) together with habitat conditions (depth to groundwater) will interactively determine the fraction of transpiration derived from groundwater at the stand level. Integrated over a large area, the contribution of soil water to transpiration in these forests can be substantial, yet easily misrepresented in scaling algorithms. Results of this study indicate that water balance calculations in riparian forests from semi-arid regions should take into consideration species-environment responses within the heterogeneous floodplain ecosystem.

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Table 1. Depth to groundwater (m) from the ground surface at the three study sites along the San Pedro River, Arizona in 1997. Data were obtained from a single well that penetrated the local floodplain groundwater at the perennial and intermittent site. Data at the ephemeral study site are an average of 2 wells. All wells were located within 10 meters of the stream channel.

Month	Perennial	Intermittent	Ephemeral
Feb.	--	2.28	3.86
Mar.	0.95	2.27	3.90
Apr.	1.98	--	4.21
June	1.42	2.61	4.43
July	2.43	3.32	4.69
Aug.	2.08	2.67	4.48
Sept.	1.91	2.53	4.31
Average	1.8	2.61	4.26

Table 2. Percentage of xylem water (± 1 SE) derived from shallow soil layers in August after a monsoon rain event. Percent shallow soil water was calculated with a 2-compartment mixing model (Eqn. 1). Normal type indicates the percent of water derived from shallow soil layers with local floodplain groundwater as an end member of the model. **Bold face** type indicates an estimate based on an average of regional groundwater and local floodplain water. Different letters indicate significant differences between the ephemeral tributary and the perennial reach of the San Pedro River, Arizona.

Species	Perennial Stream Site			Ephemeral Stream Site		
	June	July	August	June	July	August
Salix gooddingii	0	0	0	0	0	0
Populus fremontii	0	0	8 ± 8 A	0	0	26 ± 7 B
			16 ± 2 A			**33 ± 7 B**
Prosopis velutina	0	0		0	0	52 ± 5
						57 ± 7

Table 3. Percentage of xylem water ($\pm$ 1 SE) derived from shallow soil layers in August after a monsoon rain event for trees along an intermittent reach of the San Pedro River, Arizona. Percent soil water was calculated with a 3-compartment linear mixing model [Eqn. 3] for species whose mean $\delta^{18}O$ values were significantly different than that of groundwater ($p < 0.05$).

Intermittent Stream Reach			
Species	% shallow soil water	% deep groundwater	% shallow groundwater
Populus fremontii	9 ± 4	97 ± 16	-5 ± 13
Prosopis velutina	30 ± 14	3 ± 27	67 ± 40

Figure Captions

Figure 1. Mean $\delta^{18}O$ values of *Salix goodingii, Populus fremontii*, and *Prosopis velutina*, regional groundwater, floodplain groundwater, and precipitation during the 1997 growing season along perennial, intermittent and ephemeral reaches of the San Pedro River in southeastern Arizona. Vertical bars represent $\pm$ 1 SE of the mean.

Figure 2. δD - $\delta^{18}O$ values from trees, soil, groundwater, and rainfall in August 1997 along perennial and intermittent reaches and an ephemeral tributary of the San Pedro River in southeastern Arizona. Fitted line is the global meteoric water line (GMWL) ($\delta D = 8.31 * \delta^{18}O + 10.8$) (Clark and Fritz 1998). Soil water was extracted from 10-, 25-, and 100- cm depths.

Figure 3. Gravimetric soil water content (θ_g) and soil water $\delta^{18}O$ at 5-, 10-, 25-, 50-, and 100-cm depths in June prior to the onset of the summer 'monsoon' rainy season, and August after a large precipitation event. The arrows on $\delta^{18}O$ plots indicate the $\delta^{18}O$ values of local floodplain groundwater in June (*open arrow*) and August (*closed arrow*). Soils were sampled in 1997 along a perennial, intermittent and ephemeral reach of the San Pedro River in southeastern, Arizona. Horizontal bars represent 1 SE of the mean and are presented when possible with the exception of soil $\delta^{18}O$ values sampled in June.

Figure 4. The relationship between depth to groundwater and the percentage of plant transpiration water derived from shallow soil water in August after a monsoon rain event for *Salix gooddingii*, *Populus fremontii*, and *Prosopis velutina* sampled along the San Pedro River in Arizona.

Figure 5. Mean predawn leaf water potential (Ψ_{pd}) of *Salix gooddingii*, *Populus fremontii*, and *Prosopis velutina* along perennial and intermittent reaches, and an ephemeral tributary of the San Pedro River in southeastern Arizona in 1997. Horizontal bars represent 1 SE of the mean.

Figure 6. Relationship between mean $\delta^{18}O$ and mean predawn leaf water potential (Ψ_{pd}) at each sampling period over the 1997 growing season for *Salix gooddingii*, *Populus fremontii*, and *Prosopis velutina* at a perennial reach and an ephemeral tributary of the San Pedro River in southeastern Arizona. Horizontal and vertical bars represent ± 1 SE of the mean. Fitted lines are the statistically significant regression relationships for a given species ($\alpha = 0.05$).